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Jack pine budworm (choristoneura pinus) effects on fuel loading and resulting fire risk

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JACK PINE BUDWORM (CHORISTONEURA PINUS) EFFECTS ON FUEL LOADING AND RESULTING FIRE RISK

by

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ABSTRACT

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Plots were done in various locations to determine the effect of the jack pine budworm on fire frequency, intensity and severity in Northwestern Ontario. The infected plots were measured near Bak Lake attack base in the Red Lake district where stands have been heavily infected with budworm and defoliated. The control plots of healthy mature jack pine were measured in stands north of Ignace. More mortality of jack pine trees was recorded in infected sites however fuels, including downed-woody debris and organic forest floor layers, were generally still greater on mature sites of jack pine. This may be due to the timing of disturbances, like wildfire, on mature sites compared to the insect outbreaks on jack pine budworm infected sites. This information can be useful in determining resulting ignition risk in infected stands as well as fire behaviour if fires spread.

ACKNOWLEDGMENTS

I would like to thank Dr. Wang for helping put together this document, Dr Leitch and Dr. Meyer for teaching us all how to properly write an undergrad thesis. As well, Mathew Corbett for providing me the data and opportunity to learn about this topic, and my manager Travis Gamble for encouraging me to become involved in this project.

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INTRODUCTION

Forest pests have become of topic of interest and growing concern among forest managers and researchers. Insects can have detrimental effects on forests which can impact natural functions and services as well as the forestry industry harvests. As insect ranges expand, ecosystems with little or no defense adaptations may suffer as pest populations reach outbreak levels. Within industry, loss of entire stands due to severe outbreaks may cause financial strain. The jack pine budworm, *Choristoneura pinus* (*Lepidoptera: Tortricidae*), is an insect in the boreal forest which has recently become a topic of concern to forest professionals. Studies indicate that with stand defoliation and mortality due to the jack pine budworm, wildfire incidence increases. The objective of the research and data collected in this document was to determine how defoliated jack pine stands impact fuel volumes and availability and the resulting risk of wildfire occurrence and behavior. Several sites in Northwestern Ontario were selected and surveyed to compare volumes of forest floor litter, standing dead and live tree densities, size and crown densities of mature healthy jack pine sites and budworm infested sites. The field data was collected from infected stands in the Red Lake district and unaffected stands in the Ignace area. This research was conducted by a team from the Aviation Forest Fire and Emergency Services (AFFES) department of the Ministry of Natural Resources and Forestry (MRNF) during the 2019 fire season.

The hypothesis of this test is that the defoliation caused by jack pine budworm will increase the amount of available fuels thereby increasing fire frequency, severity and intensity in jack pine stands which have experienced severe jack pine budworm infestations.

Forest floor litter fuels, including coarse and fine downed woody debris were found to be more abundant in some stages of decay on mature sites than on budworm infected sites. As well, greater volumes of coarse downed woody debris and moss and litter (M/L) layer fuels were found on mature jack pine sites. The varying levels of litter in different stages of decay and in different forest floor layers may be attributed to the time since a fire disturbance has occurred. It was expected that budworm infested sites would have more forest floor fuels, however if the healthy stand has accumulated fuels over a longer period of time and the budworm outbreak was more recent, it may explain these results. In these tests, a greater duff layer in the mature stands may indicate that these stands were more receptive to lightning, and ground fires may spread more easily than in the budworm infested sites.

While forest floor fuels may be less abundant on infested sites, these sites were dominated by standing dead trees. These larger fuels may facilitate a ground or surface fire to spread and become a severe crown fire, consuming a great deal more matter. As well, in the absence of fire, these standing dead trees will add to the forest floor fuels in time as they breakdown and enter later decay classes.

This document outlines the procedures and results of the research conducted. Background information regarding the jack pine budworm and its known influence on wildfire activity is also included. The literature review provides additional information on the jack pine budworm, discussing stages of development, behavior and range. Fire ecology and behavior in the northern boreal region involving insect interactions are also discussed.

This information can be used in predicting fire occurrences in an area as well as the resulting fire behavior. Understanding the lifecycle and movement of this insect maybe be useful in determining defense mechanisms for forest managers in order to control the spread and damage of the jack pine budworm.

LITERATURE REVIEW

The following literature provides background information on the jack pine budworm, fire ecology in the Boreal forest of Northwester Ontario and insect defoliation impacts on forests in relation to fire. Jack pine budworm life cycle, range and behavior are all factors influencing jack pine stand survival and overall health. The boreal is a fire driven ecosystem which relies on wildfire for many ecological services and forest succession. Fire and insects may work in unison to promote forest succession and stand rejuvenation. Episodic outbreaks of defoliating insect species influence the risk of fire ignition, fire behavior and intensity. A balance must be maintained in this cycle as delays or intensity shifts of either process may trigger a positive feedback loop causing catastrophic disturbances. Fire management, prediction and control must be adaptable and understanding of insect regimes.

Jack pine budworm

Species is native to North America, ranging from Alberta to Nova Scotia within Canada (Figure 1), and is considered one the most important jack pine defoliators. It belongs to the family *Tortricidae,* order *Lepidoptera*, the second largest order, and class *insecta* (McCullough 2000). Severe outbreaks were first recorded in Northwestern Ontario in 2004 (BioForest Technologies Inc. 2009). Outbreaks in western provinces were recorded as early as 1922 before infected areas were routinely surveyed in 1936 as part of the Forest Insect Survey (Canadian Journal of Forest Research 1988). Budworm activity impacts the growth and overall quality of jack pine but is not limited to jack pine and may also feed on reed, white and Scots pine. Spread across the jack pine range, epidemic populations found mostly in the Great Lakes region, central and northwestern Ontario, Manitoba and Saskatchewan (Sask. Ministry of Env n.d.).

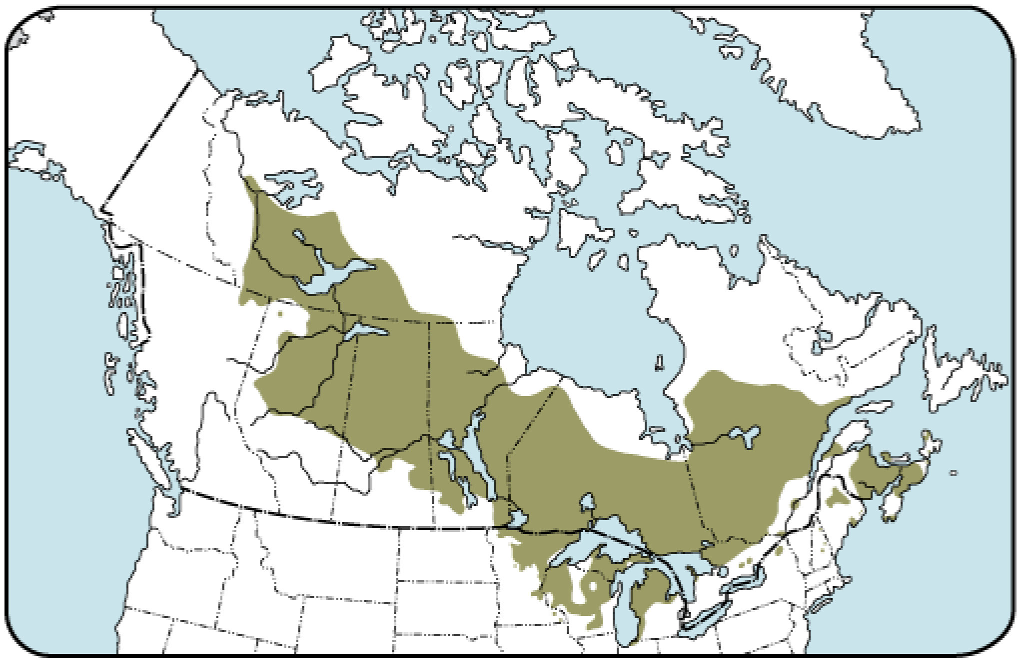

Figure 1. Jack pine range (NRCan)

Jack pine budworm may have six or seven instars throughout their life cycle. Adult moths have rust coloured forewings with grey white patches spanning 15 to 28 mm. Adult moths lay approximately 40 eggs in two or three overlapping rows along host pine needles mid-July to early August. Eggs hatch about 10 days later and the new larvae remain protected under the bark in a silken web, or hibernacula, for the duration of the winter. Mature larvae range between 20 to 22 mm in length (Figure 2). Their body reddish-brown with yellow sides and two rows of white dots running along their back. In July and august, pupae forms on the shoot or among needles and are 12 mm long, green later becoming a dark reddish brown.

Figure 2. Mature Choristoneura pinus larvae (NRCan)

Larvae emerge late May to early June and begin feeding on the pine trees male pollen flowers, before moving on to the needles of new shoots. Signs of feeding include partially chewed needles and remnants of spun silk which can give a red brown appearance. Defoliation may result in discolouration and browning throughout a stand, and this is most severe in the first year. The upper crown may be consumed, and lead to growth loss, top kill and eventually mortality in as little as two to three years during a moderate to severe infestation (Sask. Ministry of Env., MNRF, Manitoba conservation, MacQuarrie 2013).

Outbreaks may last from two to four years depending on weather conditions, parasites and other factors that may limit pollen production in pines. Outbreaks usually occur in 6 to 12-year intervals. Surviving trees following a disturbance become more susceptible to top kill and tree mortality during next infestation. Outbreaks and defoliation are more severe in mature jack pines compared to immature pines (McCullough 2000; Volney 1998).

The number and availability of pollen cones, which varies season to season, greatly impacts the survival, population and therefore damage caused by the budworm. Control measures include the bacterial spray Bacillus thuringiensis kurstaki (Btk), and tebufenozide (Mimic). These are the only insecticides registered in Canada. Natural enemies of the JPBW include parasitoids, predators and pathogens. The JPBW parasitoid guild includes a variety of species like hymenopterous parasitoids, dipterous species, hyperparasitoids. These populations heavily influence the dynamics of outbreak cycles. Parasitism is more severe of late-instar larvae and pupae rapidly leading to the decline or collapse of a population. The most common predator of the budworm includes the chipping sparrow, who will feed larvae and pupae. Most other insectivorous birds feed on fifth-instar or older budworm larvae. Some invertebrates, like ants, feed on larvae and pupae dislodged from trees. As well, insectivorous shrew populations have been recorded to increase in response to outbreaks; however, feeding was not directly observed. Pathogens may be associated with unknown late-instar mortality or reduction in egg mass size. (Sask. Ministry of Env., MNRF, Manitoba conservation, MacQuarrie 2013; McCullough 2000).

Fire behavior in the boreal

Wildfire is an integral ecological process in the boreal forest. Fire is fundamental in maintaining diversity and successional processes of ecosystems. Ecosystems are constantly changing with disturbances, either fire, insect or windthrow; however, human activity, including European settlement and the fire exclusion policy of the early 1900s, have interfered with natural disturbance regimes.

In Ontario, fire is the primary natural disturbance which influences regeneration, composition, structure and spatial distribution of a forest. This is done as fire reduces competition, creates seedbeds, releasing previously unavailable nutrients, and triggering seed release or vegetation reproduction. Fire release nutrients from burning organic matter and may indirectly release minerals through increased decomposition rates or remaining litter, erosion of soils and spalling of rocks. Soil acidity is also reduced for a short period following a fire. Post-fire conditions may facilitate improved productivity, seedling establishment or flowering with increased sunlight, and improve seed dispersal with increase wind and surface water flow. Many herbs, shrubs and grass populations rise rapidly post-fire, while tree regeneration varies by species. Wildfire consumes the carbon components of litter and restores balance in over-mature stands when organic matter build up exceeds decomposition (MacQuarrie 2013; McCullough et al.1998; Wright & Heinselman 2014).

The rate and amount of succession and diversity among stand structure is determined by the fire regime. The fire regime includes the fire return interval, rotation, intensity and severity of a disturbance. In a natural fire regime, the fire disturbance is constant driving force shaping the landscape. Fire suppression in the 19th and 20th century has interfered with the fire regime, lengthening fire return intervals and rotations, and so ecological services are not completed (MacQuarrie 2013; McCullough et al.1998)

There are three types of fires: surface, ground and crown fires. Each describes the fuel the fire is primarily supported by. Surface fires burn only the surface of the fuels on the forest floor, ground fires burn deeper into the duff layers and down trees, and crown fires consume the crown fuel layer, along with surface fuels. Crown fires are of the most concern in this report as the foliage and crown fuels are impacted most by defoliating insects, as well these intense, possibly stand replacing fires have a significant impact of the ecosystems they occur in (Stocks et al. 2004; Van Sleeuwen 2006).

Tree species react differently to forest fires, with unique coping and regeneration strategies and forest stands have different fire regimes. Conifer trees, generally, are more flammable and these stands may have a shorter fire return interval than deciduous trees. Fuel availability influenced by the weather, amount of precipitation, humidity, accumulation since last fire, extant of damage from insects and disease and stand age. Fire regimes in the boreal are usually short, averaging 20 years fire return interval for jack pine to 150 year for cedar and hardwoods in lowlands, resulting in a forest mosaic composed of even-aged pure or mix wood stands at various successional stages. However, lowland species fire cycles may range from 100s to 1000s of years as they are mainly influenced by surrounding upland fuels and intensities. Large, stand replacing fires may create a homogenous effect in topographical units on a landscape, while smaller frequent fires, like those suppressed in the intensive management zone, created a patchier, and variable effect (Van Sleeuwen 2006).

Jack pine is a wide-ranging species and major component of the boreal forest. Fire cycles greatly determine jack pines occurrence, distribution and stand structure. Fire intensity are generally the greatest in jack pine dominated stands and they exist in fire prone forests. This is because of their serotinous cone which require intense (exceeding 50^{oC}), like from that of a wildfire, to open and full exposed mineral soil seedbed to germinate. Mineral soil allows young roots to reach a steady supply of moisture in forest litter and humus. Higher temperatures open cones faster and this risks seed damage or mortality and threatens viability. Herbaceous growth in the year following fire offers some shade without competition, then later direct sunlight is required for seedling growth. Post-fire seed release occurs immediately, although germination is delayed (de Groot et. al 2004; Ahlgren & Ahlgren 1960; Gauthier 1996).

Fire and Insects

An insect disturbance and fire change how a forest adapts overtime in relation to nutrient cycling, succession and other ecological processes. This in turn may have consequences for productivity and biodiversity within a stand or ecosystem. Fire may kill insects in a stand or alter the composition, soil acidity, overstory cover, species, in a way that is unsuitable for some insects. Although many insect species in the boreal are adapted to wildfire and are able to survive or recolonize following a fire disturbance (McCullough et al.1998).
Just as fire effects insects, insect disturbance may influence fire behavior and occurrence. By causing tree mortality, insects facilitate the accumulation of woody debris like dead tops, foliage and downed trees, as well as opening the canopy. This combination of actions increases the amount of available fuel while decreasing fuel moisture. The lower fuel moisture results in an increased risk of ignition, as fine fuels and duff layers are more lightning receptive. If ignition occurs, the accumulations of fuels may result in increased fire intensity, depth of burn and spread. The initial spread index (ISI) is partly determined by the fine fuels and is used to predict a fires rate of spread (ROS). The lower fuel moisture and fuel build up can lead to an increase in the ROS and the overall fire size (McCullough et al.1998; Perrakis et al. 2014).

With increased fuel loading, due to tree mortality and top kill, more intense crown fires can occur in a stand. Higher temperatures in crowns may reduce the number of viable seeds left following a disturbance (Kourki et al. 1997).

Patterns of moderate insect outbreaks with low-intensity surface fires may be beneficial to some areas to limit fuel accumulations and delay large stand replacing fires. Frequent, small, less intense surface fires would create patches of coniferous dominant stand, allowing some area to convert to an old growth or deciduous mixwood stand. Insect outbreaks not regularly followed by fire, or widespread infestations may lead to intense stand replacing fires, opening serotinous jack pinecones, exposing mineral soils and eliminating competition. A dense forest of young jack pines trees is the result (McCullough et al.1998).

Just as insect outbreaks leave forests susceptible to fire, fire leaves trees weakened and vulnerable to insects. This weakness in surviving trees is beneficial to wood and cone-boring beetles. However, some defoliators may only attack mature stands (McCullough et al.1998).

Fire suppression in north America has interrupted the fire-insect relationship and allowed insect outbreaks occur uninhibited. While outbreaks are periodic, more over-mature conifer stands, vulnerable to insect attack, currently exist allowing insect populations to increase rapidly, shorter outbreak intervals, widespread mortality in more stands. In late succession mixedwood stands, insects may also feed outside their host range and kill more trees, for example the mountain pine beetle will attack ponderosa pine in mixedwood stands with mountain pine (McCullough et al.1998).

Fire behaviors in stand effected by insects is less predictable than unaffected stands. More research must be done in the field to accurately estimate fire intensity and spread in these forests in order to better manage these disturbances. As insect outbreaks become more severe, the need to understand the adapted fire dynamics is more important for managing tree species, protecting values and maintain ecological processes.

MATERIAL AND METHODS

Establishing Field Plots

During the month September ten study sites (5 JPBW affected and 5 unaffected stands) were chosen in the Boreal Forest of northwestern, Ontario, where areas of moderate to severe defoliation from JPBW have occurred for the past 2-3 years according to Ontario's annual FIDS program. The affected study area resides from the Whiskey Jack Forest to the northern border of the White Feather Forest and plots were established in proximity to Bak Lake Forward Attack Base. The unaffected stands were established in Ignace Area however, as they need to be outside of the area currently mapped as to having budworm damage. The selected stands were mature to over mature stands, with comparable individual stand ages, densities, and individual tree metrics. The affected stands should have had budworm present for 2-3 years, with evidence of recent tree mortality and/or top kill.

Figures three and four show the locations of the infected plots in the Whiskey Jack Forest and uninfected plots in the Ignace Area.

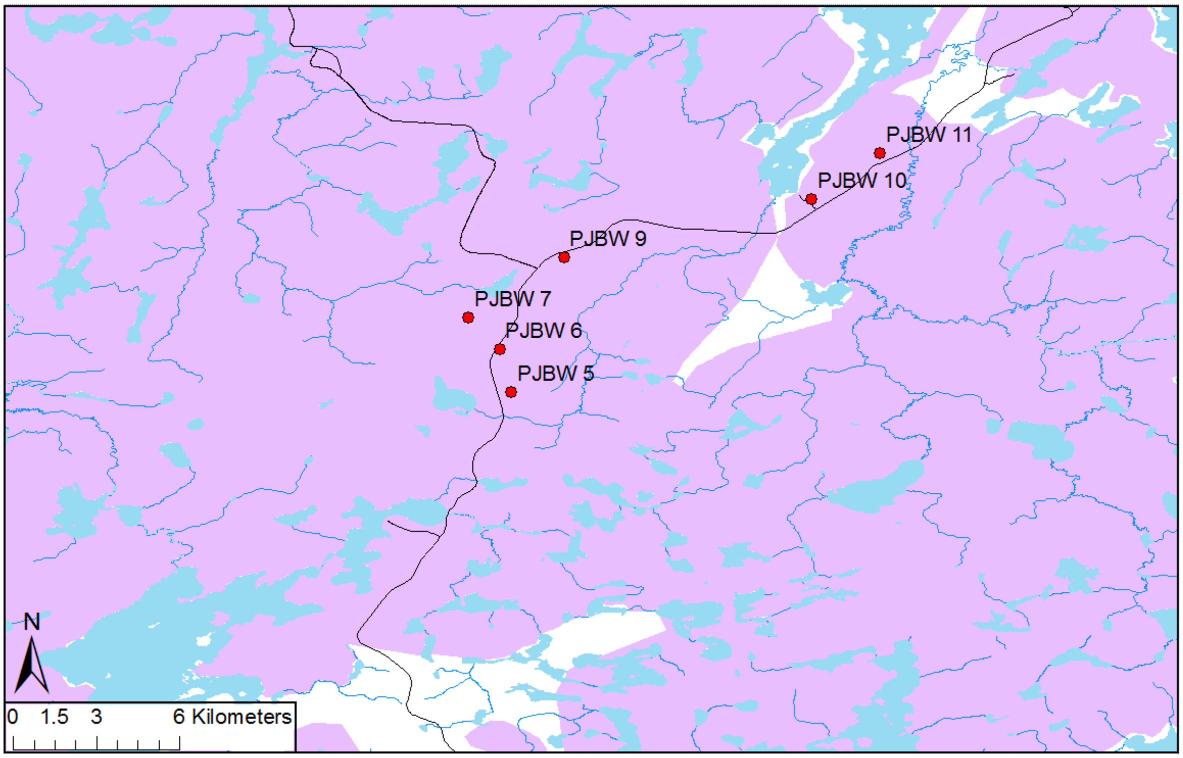

Figure 3. Map of affected plots in the Whiskey Jack Forest

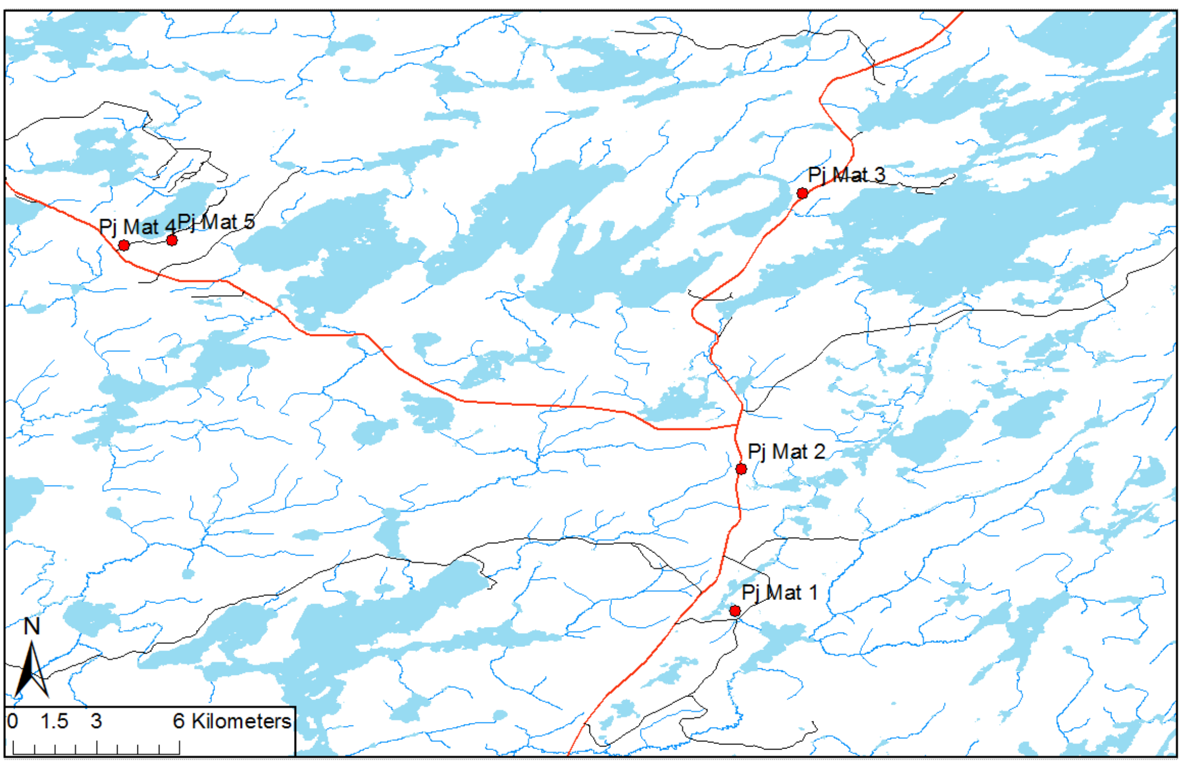

Figure 4. Map of unaffected plots in Ignace Ontario area

Five fixed area plots (400 m^2) were established in each stand, approximately 50 m apart from each other. All live and standing dead trees in each plot were measured (total height, length of dead crown if present, Dbh, percent defoliation, crown foliar density, crown fine fuel foliar moisture). Leaning live and dead trees (ladder fuels) were also be recorded. Two line transects (30 m in length) per plot were laid out perpendicular to each other intersecting at each plot centre. Coarse (intersecting diameter >7.5 cm) and fine (2.5 to 7.4 cm diameter) dead wood were recorded along each transect. Decay class will also be recorded. Four - 15 x 15 cm forest floor (LFH) samples (one in each plot quadrant) will collected, placed in a Ziploc bag, and frozen. Once back in the lab, samples will be separated in L, F, and H samples, weighed (fresh weight), oven-dried at 70oC until constant weight is achieved, and reweighed to calculate moisture content and mass per unit area.

The selected plots were chosen with special consideration as study sites may be candidate sites for proposing prescribed burns in 2020. Adequate boundaries should be a characteristics of site selection in proximity to road access.

Tree Inventory

At each site, five fixed area plots (400 m^2) were established approximately 50 m apart.
The species, status (live or dead), and Dbh of all trees > 2.0 cm in diameter was recorded. Total height and an ocular estimate of crown density was also recorded on 25 % of the live trees in each plot. Total height and decay class was also recorded for all standing dead trees.
Stand-level metrics (species composition, density, gross total volume (GTV) were calculated from the raw plot data.

Forest floor

Three 15 x 15 cm forest floor samples per DWD transect, were removed down to the start of the mineral A horizon, and depth recorded. Samples were separated by layer (moss/litter, F/H) and bagged. In the lab, fresh and dry weights were recorded to determine moisture content (%) and forest floor mass (Mg ha^{-1}).

Downed wood debris

Three 15 m transects, offset by 120°, were used to estimate DWD volumes using the line intercept method. Diameters of all dead stems > 2 cm (Fine Woody Debris: 2-7.5 cm, Coarse Woody Debris: > 7.5 cm) were recorded. For each stem tallied along the transects species, diameter at the intersection point, decay class (1 – solid, twigs intact; 2 – solid with some bark still intact; 3 – slightly punky, no bark; 4 – punky, with some penetration with pressure; 5 – advanced rot, with complete penetration with pressure), and vertical position was recorded. Volumes (m^3 ha^{-1}) were calculated using Marshall et al. (2000) equation: Where, yi = total volume in m^3 ha^{-1} based on transect i, L = length of transect in m, dij = intersecting diameter (cm) of individual pieces j to m measured along transect i.

$$y_i = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} d_{ij}^2$$

Following data collection, data analysis was conducted. Variance between sites regarding live versus dead tree volume per hectare, tree Dbh distribution, decay class and DWD were found using one-way analysis of variances (ANOVA) with the SPSS application.

RESULTS

Between sites of mature jack pine and jack pine budworm infected sites, significant differences were not found concerning measured variables inluding live tree versus dead tree volumes, significance of 0.662 and 0.731 respectively, average decay class of standing dead volume, greatest significance of 0.986 in decay class 3, or aboveground DWD volumes, significance of 0.541. The Dbh distribution of live versus dead trees on mature sites and JPBW sites was also examined. Full results of these analysis can be found in appendix A.

Mortality

Diameters of live trees varied throughout stands, but generally mature uninfected pine occurred in higher volumes than infected stems (Figure 5). Live trees with lower DBH, less than the 16 cm diameter class, and those with higher Dbh, greater than 22 cm diameter class, tallied more healthy stems than stems in budworm infected stands. Although, live trees within the 16 cm to 20 cm diameter classes were dominated by budworm infected trees. This may be due to the more vulnerable younger or older trees being more susceptible to budworm damage and mortality, decreasing infected live stems per hectare in these diameter classes. Trees under the 6 cm Dbh class, young trees which may have avoided the outbreak, show high densities indicating that there was a significant benefit from the overstory defoliation and canopy opening due to stem mortality.

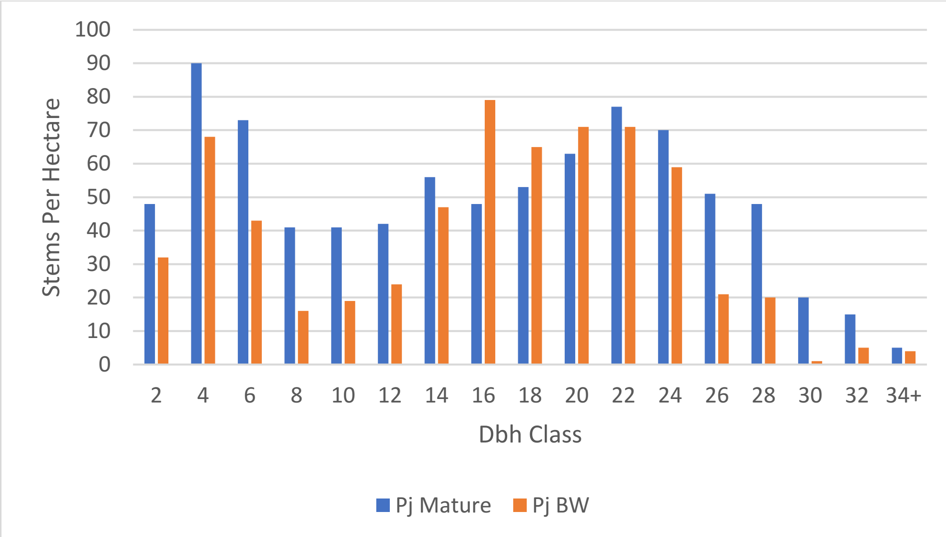

Figure 5. Live tree DBH distribution (AFFES 2019). Diameter at breast-height (Dbh) classes ranged two centimeters and live stems of infected and mature jack pine sites were counted and compared.

Among standing dead trees, most diameter classes were dominated by budworm infected trees (Figure 6). This result was expected as most stands experiencing a jack pine budworm outbreak show high degrees of mortality. The Dbh class showing the greatest mortality was 16 cm, with stem mortality decreasing in larger and smaller size classes. Trees in lower size classes may not have been affected as they were not a viable food source for the budworm at the time of the outbreak. While older trees in larger age classes may have already been less abundant on these sites, already dead or producing fewer new needles for the budworms to consume.

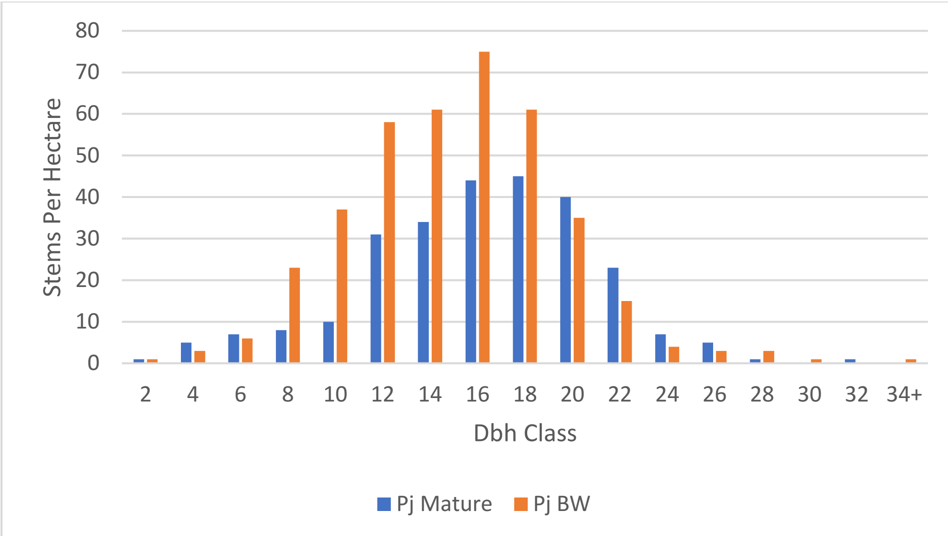

Figure 6. Standing dead tree DBH distribution (AFFES 2019). Diameter at breast-height (Dbh) classes ranged two centimeters and standing dead trees of mature and infected jack pine sites were counted and compared.

Volume

Live tree volumes of jack pine trees and total trees on site were greater on mature jack pine sites than on budworm infected sites. This indicates that there were less large living infected trees and that there were greater volumes of living trees on healthy, mature sites (Figure 7). Volumes of live jack pine trees on mature jack pine sites averaged 152.62 $m^3 ha^{-1}$ while volumes of live trees on budworm infected sited averaged 128.08 $m^3 ha^{-1}$. Total live tree volumes on mature sites was 186.66 $m^3 ha^{-1}$ and only 136.84 $m^3 ha^{-1}$ on budworm infected sites.

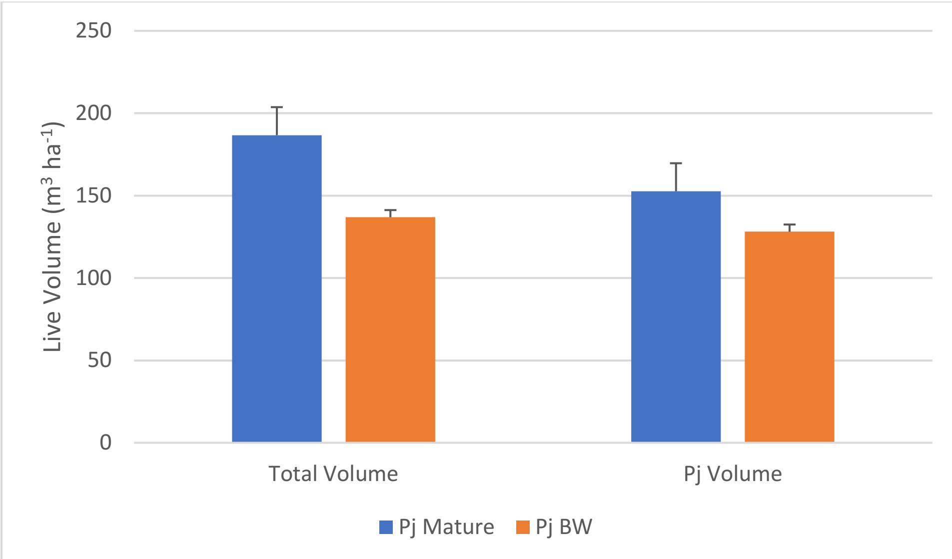

Figure 7. Volume of total live trees and jack pine (AFFES 2019). Volume per hectare of live trees on mature and infected jack pine sites.

Reversely, greater volumes of standing dead trees were found on budworm infested sites than on mature pine sites (Figure 8) of both jack pines and total tree volume on the sites. This was expected as there were far more dead standing trees on budworm infected sites than on mature jack pie sites in many size classes. Jack pine tree volumes were 30.45 $m^3 ha^{-1}$ on mature sites and 37.43 $m^3 ha^{-1}$ on budworm infected sites. Total standing dead tree volumes were 32.58 $m^3 ha^{-1}$ on mature sites and 37.53 $m^3 ha^{-1}$ on infected sites. Greater volumes of standing dead trees contributes to the accumulation of ladder fuels and facilitates crown fires in stands.

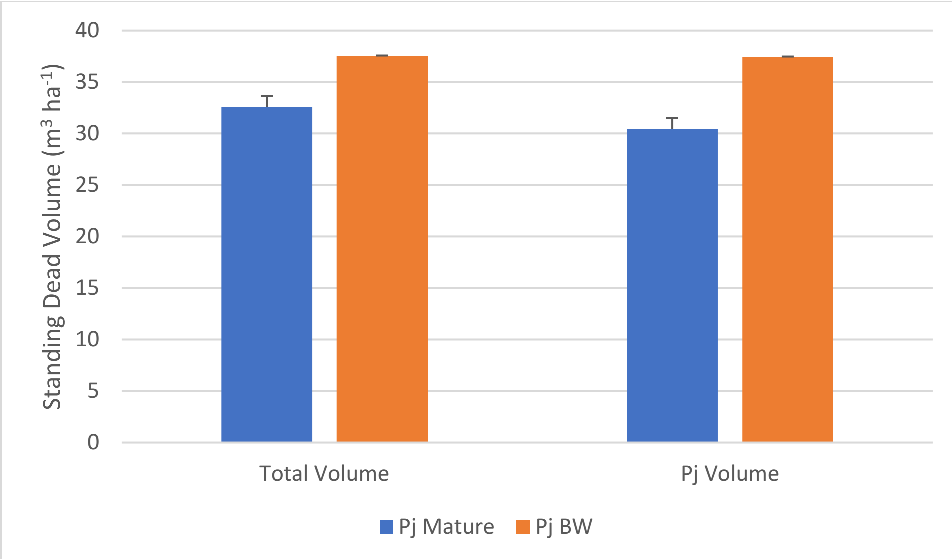

Figure 8. Volume of total dead trees and jack pine (AFFES 2019). Volumes per hectare of standing dead trees on mature and infected jack pine sites.

Crown density

Crown densities were greater on mature jack pine sites than on budworm infected sites. On average crown densities on mature jack pine sites reached 97%, compared to infected sites which on average only reached crown densities of 54% (Figure 9). This is expected as budworm consumes foliage and causes top kill and tree mortality, resulting in a decrease of crown density. Lower crown densities in stands lead to canopy gaps and greater light penetration to the forest floor. This facilitates increased germination and growth of seedlings in the understory. The high degree of defoliation from this disturbance thus initiates the succession necessary for forest renewal in the absence of fire.

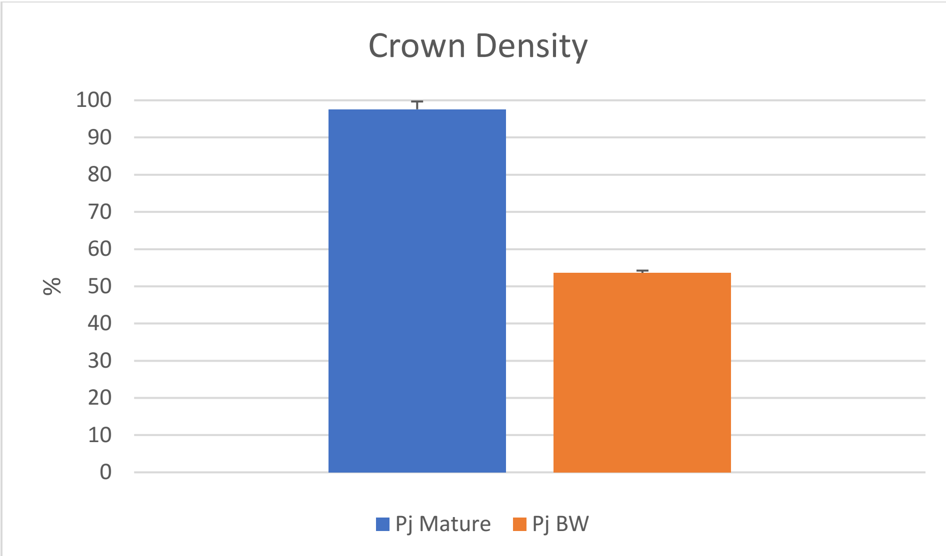

Figure 9. Crown density of mature jack pine and budworm infected pine (AFFES 2019). Percent cover of overstory, or crown closure on mature and infected jack pine sites.

Fuels

Fuels on the forest floor were expected to be significantly greater on budworm infected sites than on mature jack pine sites. On sites where budworm mortality was high, resulting forest floor layers were dryer and had a greater mass. Sites dominated by dead standing trees included F15, F13 (mature sites) 5, 6, 7, 9, 10 (JPBW sites). Silver Dollar and Elva Lake, both mature sites, had a more even mix of live and dead standing trees.

There were much greater amounts of moss and litter (M/L) fuels in budworm infested jack pine sites, averaging 1286 kg/ha, than on healthy pine sites, averaging 830 kg/ha (Figure 10). In the fibric and humic layer (F/H) a smaller difference was noted with budworm jack pine sites accumulating 35 kg/ha more fuel than mature jack pine sites.

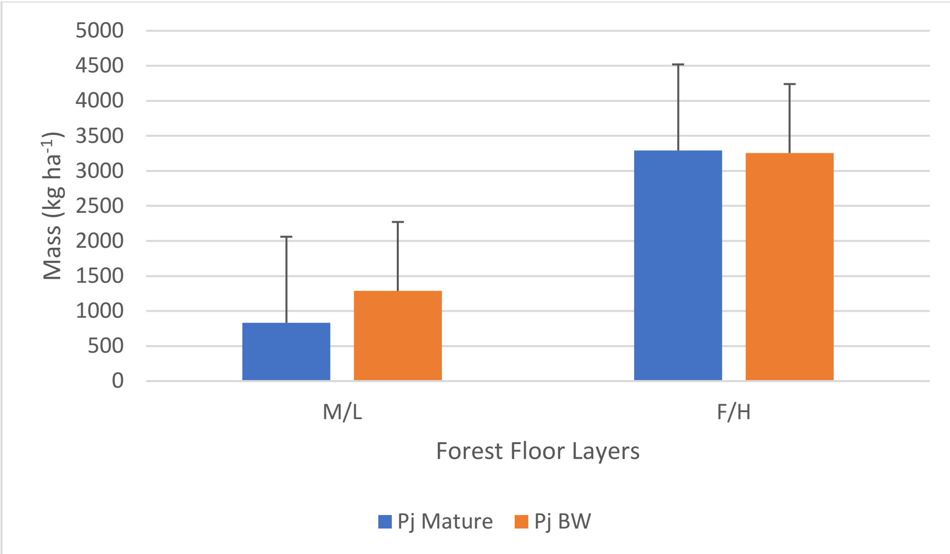

Figure 10. Average mass of forest floor layers (AFFES 2019). Mass per hectare of moss ad litter (M/L) and fibric and humic layer (F/H) of forest floor on mature and infected jack pine sites.

Greater volumes of coarse downed wood debris than fine debris were found aboveground on the forest floor on both mature and infected jack pine sites. Although more coarse debris was found on mature jack pine sites, 85.83 $m^3\ ha^{-1}$ compared to 37.80 $m^3\ ha^{-1}$. Similar volumes of fine debris were recorded on both types of sites, however greater volumes were found on jack pine budworm infected sites, 4.39 $m^3\ ha^{-1}$ on mature sites and 5.17 $m^3\ ha^{-1}$ on budworm infected sites (Figure 11). However, volumes of fine debris on mature pine sites varied greatly compared to budworm infected sites.

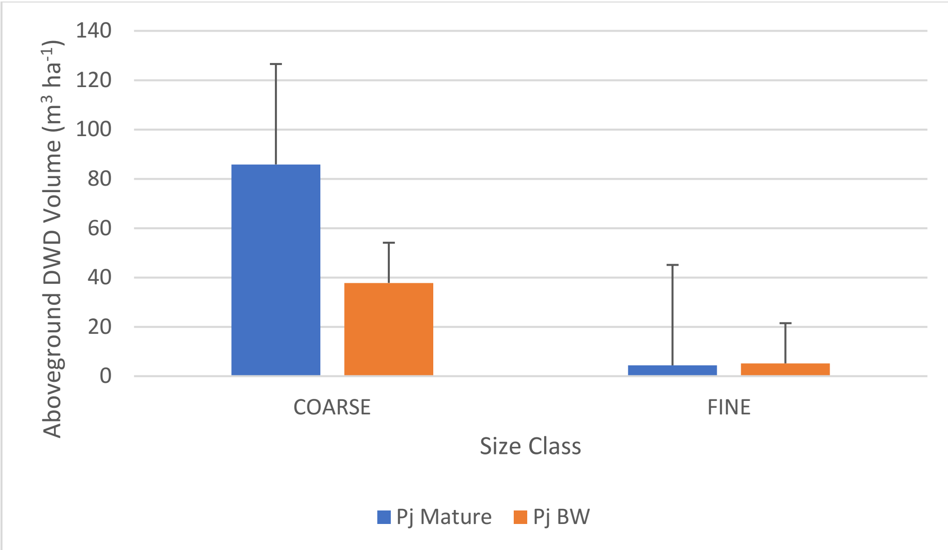

Figure 11. Average volume of aboveground downed woody debris by size class (AFFES 2019). Volume per size class, coarse woody debris: > 7.5 cm and fine woody debris: 2-7.5 cm, per hectare of aboveground downed woody debris on mature and infected jack pine sites.

Total downed woody debris displayed a similar pattern to that of aboveground downed woody debris. More coarse than fine debris was found as well as having more coarse debris on mature jack pine sites than budworm infected sites, 101.73 m^3ha^{-1} and 48.56 m^3ha^{-1}, respectively (Figure 12). Similar volumes of fine debris, more on jack pine budworm sites, 5.21 m^3ha^{-1} to 6.56 m^3ha^{-1} were recorded.

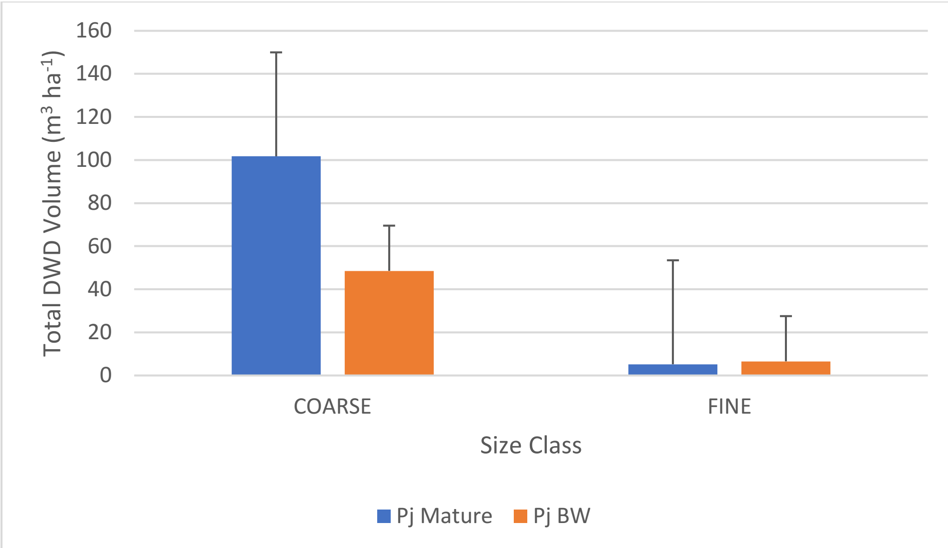

Figure 12. Total downed woody debris by size class. (AFFES 2019). Volume per size class, coarse woody debris: > 7.5 cm and fine woody debris: 2-7.5 cm, per hectare of total downed woody debris on mature and infected jack pine sites.

Decay class

Greater volumes of standing dead trees were found on budworm infected jack pine sites in decay classes one and two but did not have significant volumes in decay classes four and five (Figure 13). Greater volumes of standing dead trees were found on mature jack pine sites in decay classes three to five. More standing dead trees in lower decay classes may indicate that stand mortality of infected sites was too recent for trees to reach advanced stages of decomposition. The greatest volumes were that of decay class two on jack pine budworm infected sites, 21.56 m^3 and decay class three on mature jack pine sites, 14.09 m^3 ha^{-1}.

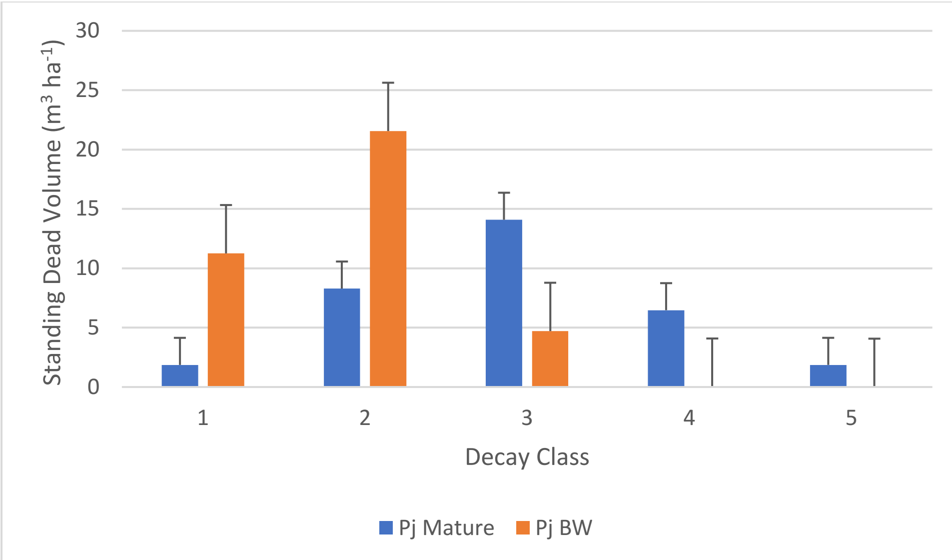

Figure 13. Standing dead volume by decay class (AFFES 2019). Decay class (1 – solid, twigs intact; 2 – solid with some bark still intact; 3 – slightly punky, no bark; 4 – punky, with some penetration with pressure; 5 – advanced rot, with complete penetration with pressure) of standing dead volume per hectare on mature and infected jack pine sites.

Aboveground downed woody debris was greater on budworm infected sites in decay classes one, 3.87 $m^3 ha^{-1}$ and two,19.12 $m^3 ha^{-1}$, than on mature sites, 0.49 $m^3 ha^{-1}$ and18.43 $m^3 ha^{-1}$ respectively (Figure 14). In decay classes three to five, mature jack pine sites had greater volumes of debris. Decay class five displayed the lowest volumes on jack pine budworm infected sites at 1.11 $m^3 ha^{-1}$. The decrease in debris volume in advanced decay classes may be a result of annual insect populations dynamics and outbreak severity. Down-woody debris may not have been decomposing long enough to qualify as class five decay (advanced rot).

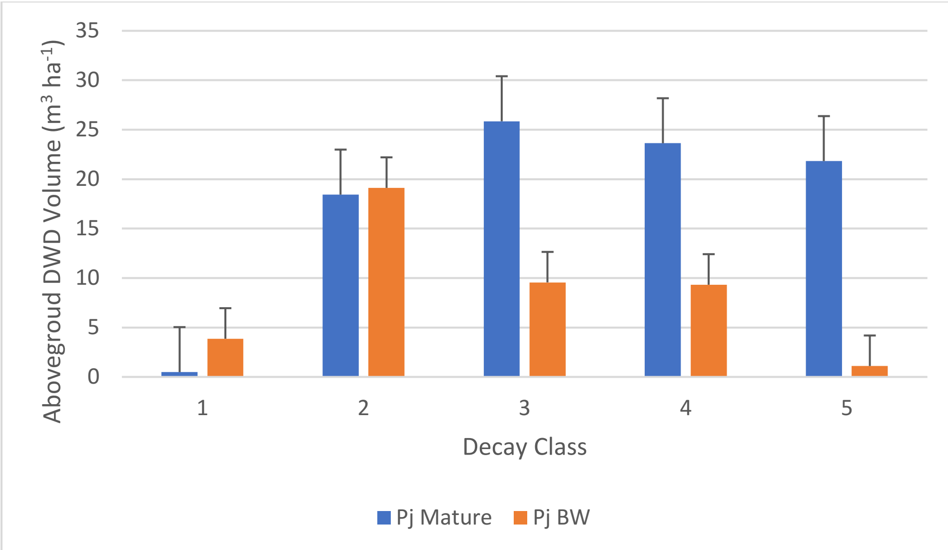

Figure 14. Aboveground downed woody debris by decay class (AFFES 2019). Decay class (1 – solid, twigs intact; 2 – solid with some bark still intact; 3 – slightly punky, no bark; 4 – punky, with some penetration with pressure; 5 – advanced rot, with complete penetration with pressure) of aboveground downed woody debris volume per hectare on mature and infected jack pine sites.

Within mature jack pine sites, total volume of downed woody debris increased per hectare with decay class, while budworm infected sites varied with decay class (Figure 15). On mature jack pine sites, the greatest accumulation of volume was 36.62 $m^3\ ha^{-1}$ in decay class five. On budworm infected sites the greatest volumes of down-woody debris were 19.14 $m^3\ ha^{-1}$ in decay class two. The increase in woody debris with decay class on mature jack pine sites may indicate that there has been an extended time period since a stand replacing disturbance, allowing fuels to breakdown and accumulate reaching advanced stages of decomposition. Meanwhile, volume of debris on the jack pine budworm sites oscillates as decay class advances, this may be as a result of varying degrees of defoliation year to year.

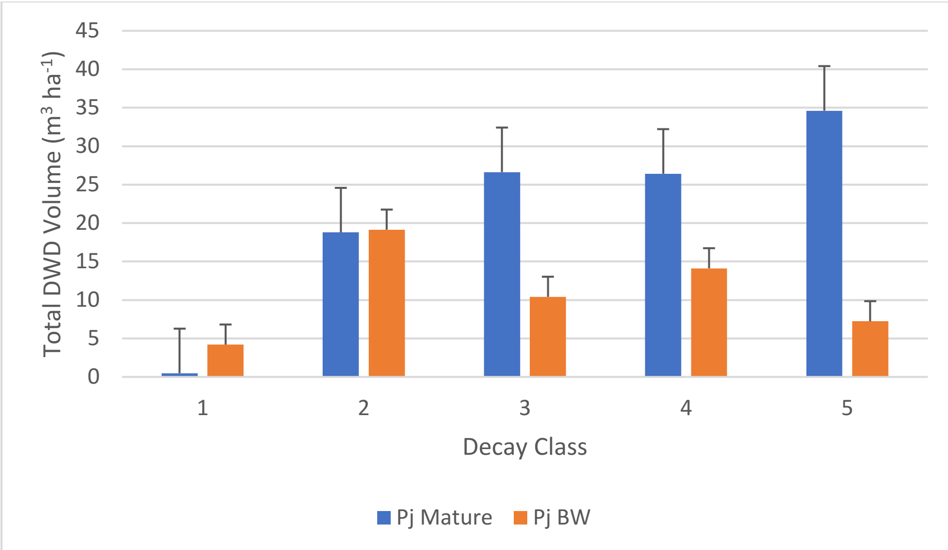

Figure 15. Total downed woody debris by decay class. (AFFES 2019). Decay class (1 – solid, twigs intact; 2 – solid with some bark still intact; 3 – slightly punky, no bark; 4 – punky, with some penetration with pressure; 5 – advanced rot, with complete penetration with pressure) of total downed woody debris volume per hectare on mature and infected jack pine sites.

DISCUSSION

It was assumed that sites which had experienced a recent insect disturbance would have an abundance of available fuels compared to mature, uninfected stands. With more stem mortality and defoliation, surface fuels and ladder fuels would accumulate and become drier due to canopy openings creating ideal conditions for wildfire ignition. The results however displayed in greater amounts of tree mortality within stands, but available fuels were not significantly higher, or higher at all, on JPBW site than mature jack pine sites.

The densities of standing dead trees in a stand may have a more significant impact on crown fires as ladder fuels on these sites are drier and more easily consumed. This in turn intensifies the fire and may greatly increase the rate of spread resulting in a larger fire area and more hectares burned. As overstory trees are defoliated and killed, increased sun penetration to the forest floor caused by canopy gaps facilitates germination and growth of seedlings and stems present following outbreak, as well as decreases in the crown density cover will attribute to this growth. As well, jack pine budworm prefers mature trees with abundant pollen over juvenile trees and so these trees are now able to grow freely and assume the role of overstory trees in these stands.

On infected jack pine sites it was expected that available fuels, including volume of standing dead trees, downed-woody debris, and mass of organic forest floor layers, both moss and litter and fibric and humic layer, would far exceed those of healthy mature jack pine sites. These expectations were not met for all factors, particularly volumes of downed-woody debris, both fine and coarse materials were lower on infected sites than on healthy sites. Although greater numbers, by size class, and volumes of dead standing trees were greater on infected sites than on healthy mature jack pine sites.

Ground level fuel, like the down woody debris, volumes were generally greater on mature jack pine sites rather than budworm infested sites. This could possibly be due to a debris accumulation in these stands from long fire return intervals. Both fine and coarse debris are important in fuel loading as they impact lightning receptiveness, depth of burn and rate of spread of surface fires, along with favorable weather conditions. These unpredicted results of greater forest floor fuels on uninfected sites may be attributed to the outbreaks on budworm infested sites having been more recent than latest disturbance on mature jack pine sites. The greater fuel and duff layer volumes on mature jack pine sites would then be a result of an increased build up or accumulation of organic matter. If the disturbance at the infested sites was more recent, less biomass would be available to accumulate, and standing dead trees may not have had sufficient time to breakdown and become forest floor fuel. An unbiased comparison between stands may require sites which have experienced different disturbances, one insect and one fire, at more similar times.

The increase in organic material and litter on the forest floor caused by insect facilitating tree decay and mortality will cause an accumulation of fuels. The open canopy created by defoliation allows for direct sun penetration and increased wind which dry fuels. The combination of these factors, a buildup of fuels and reduced moisture, create optimal conditions for ignition and fire spread within a stand. Defoliation and insect disturbance are likely to result in greater wildfire risks on infested stands. Wildland fire fighters and fire management personnel can use this information to more accurately predict fire behavior and spread. This will aid in planning, decision making as well as determining safety risks to better control wildland fires in the Northwest region.

LITERATURE CITED

Ahlgren, I. F., & Ahlgren, C. E. 1960. Ecological effects of forest fires. The Botanical Review, 2:4 483-533 pp.

BioForest Technologies Inc. 2009 Forest Health Update – Fall. 2009. http://www.bioforest.ca/documents/index.cfm?fuseaction=viewFile&fileid=89&catid=16&subSiteID=0

De Groot, W. J., Bothwell, P. M., Taylor, S. W., Wotton, B. M., Stocks, B. J., & Alexander, M. E. 2004. Jack pine regeneration and crown fires. Canadian Journal of Forest Research. 34:8. 1634-1641 pp.

Gauthier, S., Bergeron, Y., & Simon, J. P. 1996. Effects of fire regime on the serotiny level of jack pine. Journal of Ecology. 539-548 pp.

Government of Ontario. 2014. Jack Pine Budworm. Web. https://www.ontario.ca/page/jack-pine-budworm

Kouki, J., McCullough, D. G., & Marshall, L. D. 1997. Effect of forest stand and edge characteristics on the vulnerability of jack pine stands to jack pine budworm (Choristoneura pinus pinus) damage. Canadian Journal of Forest Research. 27:11. 1765-1772 pp.

MacQuarrie, C. 2013. Predicting Jack Pine Budworm Defoliation. Canadian Forest Services. Frontline Express. Bulletin 72. NR Can.

Manitoba Conservation. N.d. Gov. of Manitoba. Web. https://www.gov.mb.ca/sd/forests_and_lands/forestry/forest_health_renewal/index.html

McCullough, D., Werner, R. and Neumann, D. 1998. Fire and insects in northern and boreal forest ecosystems on North America. Annual Review of Entomology. 43: 107-127pp.

McCullough, D. G. 2000. A review of factors affecting the population dynamics of jack pine budworm (Choristoneura pinus Freeman). Population Ecology. 42:3. 243-256 pp.

Oldford, S., & Meating, J. 2010. Jack pine budworm impact assessment for the development of a jack pine budworm decision support system–2009 report. In Proc. SERG International 2010 Workshop. 9-11 pp.

Perrakis, D. D., Lanoville, R. A., Taylor, S. W., & Hicks, D. 2014. Modeling wildfire spread in mountain pine beetle-affected forest stands, British Columbia, Canada. Fire ecology. 10:2. 10-35. pp

Saskatchewan Ministry of Environment. Jack pine budworm (Choristoneura pinus pinus). Forest Pest Fact Sheet.

Stocks, B. J., Alexander, M. E., Wotton, B. M., Stefner, C. N., Flannigan, M. D., Taylor, S. W., ... & Dalrymple, G. N. 2004. Crown fire behaviour in a northern jack pine black spruce forest. Canadian Journal of Forest Research. 34:8. 1548-1560 pp.

Van Sleeuwen, M. 2006. Natural fire regimes in Ontario. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto. 143 pp.

Volney, W. J. A. 1988. Analysis of historic jack pine budworm outbreaks in the Prairie provinces of Canada. Canadian Journal of Forest Research. 18:9. 1152-1158 pp.

Volney, W. J. A. 1998. Ten-year tree mortality following a jack pine budworm outbreak in Saskatchewan. Canadian journal of forest research 28:12. 1784-1793 pp.

Wright, H. E., & Heinselman, M. L. 2014. The ecological role of fire in natural conifer forests of western and northern North America—Introduction. Fire Ecology. 10:3. 4-13 pp.

APPENDIX

APPENDIX A

ONE-WAY ANALYSIS OF VARIENCE

Live volume vs dead volume per hectare variance of Mature Pj and PJBW sites

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Live Pj m^3/ha	Between Groups	6557.563	4	1639.391	.604	.662
	Within Groups	122190.727	45	2715.349		
	Total	128748.290	49			
Dead Pj m^3/ha	Between Groups	677.820	4	169.455	.506	.731
	Within Groups	15070.019	45	334.889		
	Total	15747.840	49			

Average decay class of standing dead volume variance of Mature Pj and PJBW sites per hectare

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
1	Between Groups	298.396	4	74.599	.994	.421
	Within Groups	3227.246	43	75.052		
	Total	3525.642	47			
2	Between Groups	151.887	4	37.972	.211	.931
	Within Groups	7729.090	43	179.746		
	Total	7880.977	47			
3	Between Groups	22.787	4	5.697	.087	.986
	Within Groups	2821.641	43	65.620		
	Total	2844.428	47			
4	Between Groups	5.630	4	1.408	.098	.982
	Within Groups	615.761	43	14.320		
	Total	621.391	47			
5	Between Groups	17.686	4	4.421	.647	.632
	Within Groups	293.945	43	6.836		
	Total	311.631	47			

Average aboveground DWD variance of Mature Pj and PJBW sites per hectare

ANOVA

m3/ha

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	19202.919	9	2133.658	1.669	.541
Within Groups	1278.534	1	1278.534		
Total	20481.454	10			

JPBW Dbh distribution variance of Mature Pj and PJBW sites

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Live	Between Groups	11338.941	16	708.684	.	.
	Within Groups	.000	0	.		
	Total	11338.941	16			
Dead	Between Groups	11051.059	16	690.691	.	.
	Within Groups	.000	0	.		
	Total	11051.059	16			

Mature Pj Dbh distribution variance of Mature Pj and PJBW sites

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Live	Between Groups	7856.235	16	491.015	.	.
	Within Groups	.000	0	.		
	Total	7856.235	16			
Dead	Between Groups	4484.118	16	280.257	.	.
	Within Groups	.000	0	.		
	Total	4484.118	16			